A Multi-Objective ILP Formulation for RWA Problem in WDM Networks

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A Multi-Objective ILP Formulation for RWA Problem in WDM Networks

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Dedicated to my parents and teachers

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Certificate

This is to certify that the work in the thesis entitled ***" A Multi-Objective ILP Formulation for RWA Problem in WDM Networks"*** submitted by ***Ravi Sankar Barpanda*** is a record of an original research work carried out by him under our supervision and guidance in partial fulfillment of the requirements for the award of the degree of Master of Technology (Research) in Computer Science and Engineering, National Institute of Technology, Rourkela. Neither this thesis nor any part of it has been submitted for any degree or academic award elsewhere.

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Abstract

All-optical networks employing Wavelength Division Multiplexing (WDM) technique will be the backbone of next generation Internet. In WDM optical networks, each fiber link is logically divided into multiple non-interfering, circuit-switched communication channels known as *wavelength channels* and are identified by the length of the wave.

Routing and Wavelength Assignment (RWA) problem is a classical problem in WDM networks. It is further divided into two subproblems: *(i)* Routing, and *(ii)* Wavelength Assignment. Routing subproblem finds a route from source to destination. Wavelength Assignment subproblem assigns a wavelength to the route established by routing subproblem. The RWA problem is combinatorial by its nature and belongs to a class of difficult combinatorial optimization problems. The optimal solution to the RWA problem is found to be NP-complete and thus suited to heuristic approaches.

RWA problem is reported in the current literature as an integer linear programming problem (ILP) that typically optimizes a single objective, either minimizes the number amplifiers, the network load or maximizes the number of connections while satisfying power constraints. In this work, we formulated the RWA problem as a multi objective ILP problem. Our primary concern is to establish a loop free lightpath that is immune to signal distortion and crosstalk. An attempt is made to obtain a feasible solution using genetic algorithm (GA). The parameters considered for optimization are congestion among the individual lightpath requests, connection set up time, the number of intermediate hops traversed and the number of fibers used to honor the established connection requests. We considered ARPANET (Advanced Research Project Agency NETwork) and NSFNET (National Science Foundation NETwork) for our simulation.

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Contents

List of Figures

List of Tables

List of Acronyms

Acronym	Description
RWA	Routing and Wavelength Assignment
WDM	Wavelength Division Multiplexing
OXC	Optical Cross Connect
WXC	Wavelength Cross Connect
ILP	Integer Linear Programming
GA	Genetic Algorithm
SLE	Static Lightpath Establishment
DLE	Dynamic Lightpath Establishment
ARPANET	Advanced Research Project Agency Network
NSFNET	National Science Foundation Network

Chapter 1

Introduction

The first low-loss optical fiber was invented by Corning in 1970. Since then, it remain the worldwide market leader, offering a full line of single-mode and multi-mode optical fiber for all network applications. Today, optical fiber has been playing an important role in information transmission [24, 25]. Optical networks have many advantages that facilitate the purpose of handling large volumes of Internet traffic [66] as well as meeting the huge capacity requirement of advanced services such as voice chat, video streaming, P2P file sharing, grid computing, HDTV programming [30, 58]. Few advantages of optical fiber are listed below [17, 18, 47]:

- Optical fibers offer much higher bandwidth than copper cables.
- The transmission cost can be reduced considerably.
- Optical fibers are less susceptible to various kind of electro-magnetic interferences and other undesirable effects.

Theoretically, a single mode optical fiber has a potential bandwidth of approximately 25THz in the 1.55 micron low attenuation band. However, the demand for point to point communication per application is not typically as much. Therefore, to better utilize the capabilities of optical networks, the bandwidth of an optical fiber is divided into multiple communication channels employing wavelength division multiplexing (WDM) technology [51, 52, 53, 69, 74]. Each channel corresponds to a unique wavelength.

1.1 WDM Networks

Wavelength division multiplexing operates by dividing the low-loss regions of the optical transmission spectrum into many non-overlapping wavelengths. Each wavelength supports one communication channel that can be operated at a desired bit rate allowing multiple channels to coexist on a single fiber. It does not require nodes to synchronize to the same clock. One advantage of WDM is that no equipment needs to run faster than the bit rate of a single WDM channel, which can be chosen arbitrarily [51]. As a result, WDM is the current favorite among multiplexing techniques for optical networks.

In a WDM network, the number of wavelengths that each fiber can carry simultaneously is limited by the physical characteristics of the fiber and the optical technology used to combine the wavelengths onto the fiber and separate them off [62]. WDM is achieved by using optical transmitters and receivers at end nodes. Both lasers and light-emitting diodes (LEDs) serve as transmitters in optical networks, however, lasers are most widely used. Receivers are optical filters that separate out desired wavelengths. Tunable lasers and filters allow the wavelength of light emitted or received to be adjusted as desired.

Wavelength routing is considered as a more sophisticated and practical architecture. The nodes in wavelength-routed WDM networks are capable of routing wavelengths individually. This allows for reuse of wavelengths on routes that do not share common links. Therefore, this architecture is better suited for use in high-speed next generation telecommunication networks [35, 70].

A Wavelength Cross-connect (WXC) (also known as Optical Cross-connect or OXC) is capable of routing an incoming signal at an input port to any other output port. A wavelength cross-connecting switch is depicted in Fig. 1.1.

WDM networks use lightpath [14, 24, 47, 62, 84] to exchange information between the node pairs. A lightpath is an all optical (single-hop) logical connection that does not require processing or buffering at intermediate nodes. Fig. 1.2 shows the establishment of five lightpath requests using two carrier wavelengths in an optical network having five routing nodes and eight fiber links.

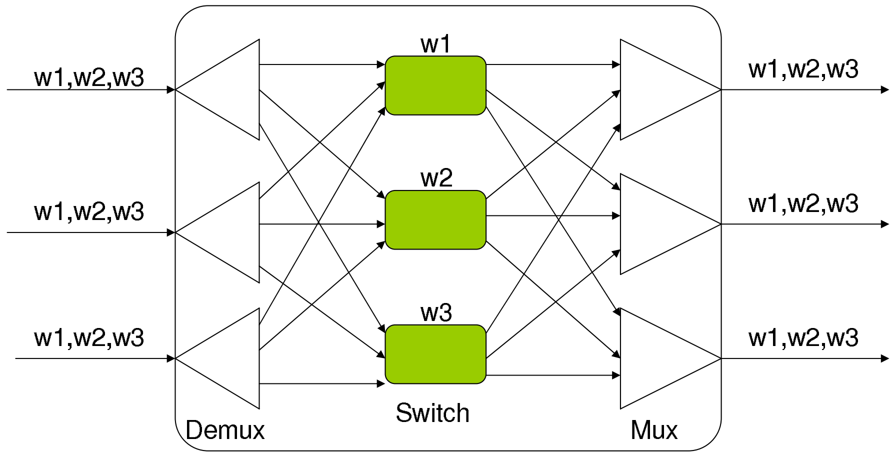

Figure 1.1: Wavelength cross-connecting switch

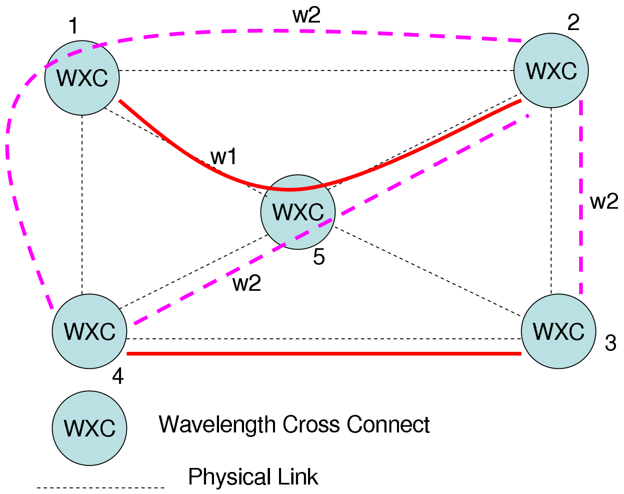

Figure 1.2: Switching strategy in WDM networks

1.2 The Routing and Wavelength Assignment Problem

Given a network topology and a set of end-to-end lightpath requests, the problem of assigning a route and wavelength(s) to these requests, using minimum possible wavelengths is known as the Routing and Wavelength Assignment (RWA) problem [20, 63, 85]. Classification of RWA problem is shown in Table 1.1.

Table 1.1: RWA Classification

Classification	RWA
Traffic Type	Static,Dynamic
Objective function	Max-RWA,Min-RWA
ILP formulation	Link-based, Path-based
Wavelength conversion	Full,Sparse,None
Fiber multiplicity	Single,Multiple
Request multiplicity	Single,Multiple

RWA problem is considered to be an NP-complete problem. Complexity of RWA problem arises from the following two facts [22, 77, 78, 81]:

(i) Wavelength Continuity Constraint: A lightpath must occupy the same wavelength on all the fiber links through which it traverses.

(ii) Wavelength Distinct Constraint: Two lightpaths must not be assigned the same wavelength on a given link.

RWA problem can have the following two variations depending upon the traffic pattern:

(i) Static Lightpath Establishment (SLE) problem: In static case, the entire set of connection requests is known beforehand and the objective is setting lightpaths for these requests, while minimizing the number of wavelengths used. Alternatively, a static RWA algorithm attempts to set up as many of connection requests as possible given a fixed number of wavelengths per fiber link. The static RWA problem can be formulated as an integer linear program which is reported to be NP-hard [4, 16, 48, 64, 85, 86].

(ii) Dynamic Lightpath Establishment (DLE) problem: In the dynamic case, a lightpath is setup only by the time a connection request arrives and it will be released after some duration. The general objective of dynamic RWA algorithms is to minimize the total number of blocked connections.

1.3 Motivation

The existing work on RWA problem reported in the literature mostly attempt to optimize a single objective function. Most of the work attempt to minimize one of the following: *(i)* the number of amplifiers [87], *(ii)* network cost [71, 83], *(iii)* congestion [39], or *(iv)* maximize the number of connections satisfying the power constraints [3]. In recent studies, the RWA problem has been modeled as a bi-objective optimization problem. Le et al. [41] have solved the dynamic RWA problem using GA where the stated fitness function simultaneously involves the path length and the number of free wavelengths in route evaluation. Banerjee et al. [7] have formulated the static RWA problem as a combinatorial optimization problem and solved it using GA. They proposed a cost function that considers average delay minimization and wavelength minimization to evaluate the fitness of a chromosome. Authors in [43, 44] have considered two network design objectives: *(i)* maximization of accepted communication requests, and *(ii)* minimization of wavelength channel requirement for routing and wavelength assignment in WDM networks.

One of the challenge faced by the network designers are to identify the parameters in order to formulate a multi-objective ILP for the RWA problem. The formulated ILP should be able to establish a loop free lightpath that has shorter set-up time, lower congestion among the individual connections, and lesser accumulated crosstalk while traversing between the source-destination node pair.

1.4 Objective of Research

With the motivation as outlined in the previous section, we identify the objectives of our research work is as follows:

- To interpret the RWA problem as an NP-complete problem
- To model RWA problem as a multi-objective optimization problem.
- Solve the above formulated ILP using genetic algorithm to optimize different network parameters under certain stated fitness functions and compare their results.

1.5 Organization of The Thesis

The thesis is organized as follows.

Chapter 1: A brief introduction to WDM networks along with the classification of RWA problem is stated in Chapter 1.

Chapter 2: A survey of the RWA problem as reported in the literature is mentioned in this chapter.

Chapter 3: In this chapter we have shown that RWA problem is an NP-complete by performing a polynomial time reduction from the 3-SAT problem to clique problem.

Chapter 4: We formulate a multi-objective ILP for the RWA problem in this chapter. The parameters attempted to optimize are congestion, route length, hop-count and the total number of fiber links used to honor all the lightpath requests.

Chapter 5: We simulate the formulated ILP using GA under different fitness functions, and the results of the simulation are compared in this chapter.

Chapter 6: Few conclusions, along with the future scope for research is mentioned in this chapter.

Chapter 2

Literature Survey

To address the RWA problem in optical networks various heuristics and meta-heuristics approaches are reported in the literature. In this chapter we make a brief survey of related work reported in the literature.

2.1 Heuristic Approaches for RWA Problem

Chlamtac et. al. [15] proposed the concept of Lightnet architecture to deal with the problem of mismatch between the electronic processing rates and the optical transmission bandwidth in WDM based wide area networks. It operates on the principle of construction and use of a virtual topology network in the wavelength domain, embedded in the original network. Their work mainly focus on the embedding of virtual networks whose topologies are regular, using algorithms which provide bounds on the number of wavelengths, switch sizes, and average number of switching stages per packet transmission. Authors have shown that the Lightnets offer substantial performance gains in comparison to conventional network architectures, in terms of increased throughput and smaller buffering requirements.

Zhang and Acampora [86] have proposed a heuristic algorithm for effectively assigning a limited number of wavelengths among the access stations of a multihop network wherein the physical medium consists of optical fiber segments which interconnect wavelength-selective optical switches. Such a physical medium permits the limited number of wavelengths to be re-used among the various fiber links, thereby offering very high aggregate capacity. Although the optical connectivity among the access stations can be altered by changing the states of the various optical switches, the resulting optical connectivity pattern is constrained by the limitation imposed at the physical level. The heuristic is tested on a realistic traffic model, and the call blocking performance of new requests for virtual connections is studied through extensive simulations and compared against the blocking performance of an ideal infinite capacity centralized switch. The authors found that for a wide range of parameters the blocking performance of the lightwave network is almost the same as that of an ideal centralized switch. From the results they concluded that the heuristic algorithm is effective and the routing scheme is efficient.

Banerjee et. al. [9] have considered the problem of designing a logical optical network topology for a given physical topology and a given traffic demand matrix between the end-users. Traffic between the end-users is carried in a packet-switched form and the objective of the logical topology design is to minimize the maximum congestion on the logical connections in the logical topology. They first provided a lower bound on the maximum congestion based on a relaxed linear programming formulation of the problem. Then they proposed an analytical model for obtaining the maximum and average logical connection loads in a given logical network topology and traffic demand matrix. The analytical model was confirmed via simulation results for several network configurations. Finally, they presented two design methodologies for constructing logical topologies in which the maximum link congestion is minimized. The first scheme maximizes total one-hop traffic while maintaining connectivity of the topology using a linear programming formulation. The second scheme starts with a fully connected topology and eliminates lightly loaded links until a topology with the desired nodal degree is obtained.

Banerjee and Mukherjee [5] have presented an integer linear programming formulation to derive a minimal-hop-distance solution to the virtual topology design problem in a wavelength-routed optical network, in the absence of wavelength-continuity constraints. The problem formulation can be used to derive a complete virtual topology solution, including choice of the constituent lightpaths, routes for these lightpaths, and intensity of packet flows through these lightpaths. They observed that adding the wavelength-continuity constraints and queueing delays makes the problem formulation more complex, thus used many simplifying assumptions in order to engineer the problem to a tractable form. They also proposed two greedy heuristics and demonstrated that these heuristics perform well with respect to the optimal solution. They studied resource-budgeting tradeoffs in the allocation of transceivers per node, and wavelengths per fiber. A simple computation provided an approximate bound regarding the number of transceivers that can be supported in a network with W wavelengths. They demonstrated how the network can equip with an optimal balance of transceivers and wavelengths, in order to derive minimal-hop-distance solutions, along with high utilization of both transceivers and wavelengths. They proposed an exact reconfiguration procedure which, for a changed traffic matrix, searches through all possible optimal virtual topologies, in order to obtain a solution which shares the maximum number of lightpaths with the previous virtual topology. The solution to the reconfiguration algorithm generates a virtual topology which minimizes the amount of switch retunings that needs to be performed, in order to adapt the virtual topology to the new traffic matrix.

2.2 Meta-heuristic Approaches for RWA Problem

Several papers have already appeared on the RWA problem, proposing various meta heuristic solutions in the design of general wide area mesh network topology that minimize the network cost.

A search of the current literature shows two recently published applications [2, 27] of fuzzy control to the RWA problem for packet-switched optical networks. Simulated annealing is used for wavelength assignment planning in [34, 67]. Genetic algorithms have been used to solve the RWA problem under different assumptions of arrival pattern and optimization objectives [3, 7, 29, 59, 60, 72, 73, 87]. One study [21] is also found in the literature that examine using tabu search to solve the static lightpath establishment problem for nonuniform traffic and another study [54] for uniform traffic. A comparison of some of the above meta heuristic approaches is available in [28]. Based on the scopes and objectives of this thesis, we focus on some studies employing genetic algorithm approaches to solve the RWA problem.

Authors in [7, 8] have formulated the Static RWA problem in optical networks as a single objective optimization problem and solved it using an evolutionary algorithm. A hybrid approach based on the k-shortest path for every source-destination pair was used to initialize the population. A special cost function based on the frequency of occurrence of an edge in different source-destination paths was used to evaluate the fitness of a chromosome. A m-point crossover is used to maintain diversity in the solution space. The wavelength assignment to lightpaths in fittest individuals is performed using a special graph-coloring technique.

The Max-RWA model has been modified by introducing limited-range wavelength converters at the intermediate nodes [59]. The optimization objective is to maximize the establishment of connection requests with least use of wavelength converters. The Max-RWA problem is formulated as an integer linear programming problem, and solved using genetic algorithm.

M. C. Sinclair [72, 73] has proposed a minimum cost wavelength-path routing and wavelength allocation scheme using a genetic algorithm / heuristic based hybrid algorithm. A cost model that incorporates dependency on link and wavelength requirements has been adopted . The hybrid algorithm uses object-oriented representation of networks and incorporates four functions: path-mutation, single-point crossover, re-route and shift-out. In addition, an operator probability adaptation mechanism is employed to improve operator productivity.

Zhong Pan [56] developed a new fitness function to solve the routing sub-problem of the RWA problem using genetic algorithm. The objective was to route each lightpath in such a way to minimize the number of wavelengths needed to honor all the static lightpaths. The secondary target was to minimize the cost in setting the lightpaths.

D. Bisbal et. al. [12] proposed a genetic algorithm to perform dynamic routing and wavelength assignment in wavelength routed optical networks with no wavelength converters. Controlling the evolution parameters of the genetic algorithm, a high degree of fairness among the connection requests was achieved by the authors. They also developed an extension to their proposed algorithm with the aim at providing protection to the lightpaths in the optical layer. The main drawback of their method is that they have considered route length as the only parameter to define the fitness function.

Le et. al. [40, 41] have proposed an improved GA to solve the dynamic RWA problem. To achieve better load balancing among individuals, they have formulated a new fitness function that simultaneously involves the path length, number of free wavelengths and wavelength conversion capability in route evaluation. They have achieved a lower blocking probability than that of the genetic algorithm proposed by Bisbal et. al. in [12].

Recent research work has employed a hybrid algorithm using Particle Swarm Optimization (PSO), inspired by an Ant System (AS) to solve the problem of dynamic RWA in WDM networks with the wavelength the continuity constraint applied [26].

2.3 Design Objectives for RWA Problem

In this section, we give a brief literature review that formalizes the RWA problem both as a single objective as well as multi objective combinatorial optimization problem.

With respect to exact solutions, the RWA problem has been formulated as an integer programming problem but most of the time those formulations have not been used for developing solution schemes as they are just intractable as soon as the size of the instances is increasing.

In previous linear formulations [42, 63, 68] for the RWA problem the paths that the source-destination pair is allowed to take had to be specified beforehand. This is called as the path formulation ILP. As the number of paths between a node pair is exponential to the number of nodes of the graph; the path formulation will have to restrict itself to a few paths per node pair. When only a limited number of paths are considered, the path formulation ILP approach may yield a sub-optimal solution. In [38, 55, 82], the authors have proposed link based ILP formulations, i.e., the constraints are defined on the links (edges or arcs) of the network. The advantage of this formulation is that we do not specify the paths beforehand, but allow the ILP solver to choose any possible path and any possible wavelength for a node pair and also the number of constraints in this formulation grow polynomially in the number of nodes.

Jaumard et al. [32] have presented a review of the integer linear programming formulations that have been proposed for the routing and wavelength assignment problem in WDM optical networks assuming asymmetrical traffic. They reported that all formulations proposed under asymmetrical traffic assumptions, both the link and path formulations, are equivalent in terms of the upper bound value provided by the optimal solution of their linear programming relaxation, although their number of variables and constraints widely differ. They proposed improvements for some of the formulations that result in further reductions in the number of variables and constraints.

2.4 Summary

In this chapter, we briefly described the relevant previous work in the area of wavelength routed optical networks using evolutionary techniques to allocate routes and assign wavelengths to the lightpath requests. The purpose of this chapter is to provide a better background and perspective of our work.

Chapter 3

RWA Problem is NP-Complete

NP problems are the class of problems for which we have no deterministic polynomial time algorithms [11]. These are the problems solvable by a non-deterministic algorithm which is basically a definitional device for capturing the notion of verifiability, rather than a realistic method for solving the problems. NP problems are classified into following classes; according to their complexity.

- NP-hard: A problem is NP-hard if an algorithm for solving it can be translated into one for solving any NP-problem. NP-hard therefore means "at least as hard as any NP-problem," although it might, in fact, be harder.

- NP-complete: A problem L is NP-complete if $L \in NP$ and for every $L' \in NP$; $L' \leq L$

To cope with NP problems; the following methods are generally adopted because the global optimum is unachievable in a reasonable time [11]:

- Dynamic Programming, Backtracking or Branch-and-Bound techniques are used to reduce the computational cost.

- The original problem is decomposed into sub-problems that have polynomial time solutions.

- Approximation algorithms are used to find an approximate solution in polynomial time.

- Randomized algorithms are used to find solution in affordable time with a high probability of correctness of the solution.

- Heuristics like greedy method, Simulated Annealing, Genetic Algorithm etc are used to produce solutions that are guaranteed to be within a certain distance from the optimal solution.

When the fiber links of an optical network support enough wavelength channels; the RWA objective relies upon minimizing the number of wavelengths required to establish all the lightpath requests. It is called Min-RWA problem. The time required to calculate the minimum number of wavelengths grows exponentially with the number of lightpath requests. Thus, for a large instance of traffic matrix; the RWA problem becomes NP.

3.1 Assignment of Wavelength Colors to Lightpaths

Under wavelength continuity constraint, assigning wavelength colors to the lightpaths reduces to the traditional graph coloring problem and the steps involved are defined as follows [4, 85, 86]:

- Construct a graph $G(V, E)$ so that each lightpath is presented by a node in $V(G)$.
- Insert an undirected edge between a pair of nodes if the corresponding lightpaths share a fiber link.
- Color the nodes of the graph G such that no two adjacent nodes have the same color and the minimum number of colors required to color the graph defines its chromatic number and is denoted as $\lambda(G)$.

In Fig. 3.1; we have considered an exemplary network where eight lightpaths are established using three distinct wavelength colors such as w_0, w_1 and w_2. An auxiliary graph $G(V, E)$ is developed for the lightpaths in Fig. 3.1 using the above explained reduction mechanism.

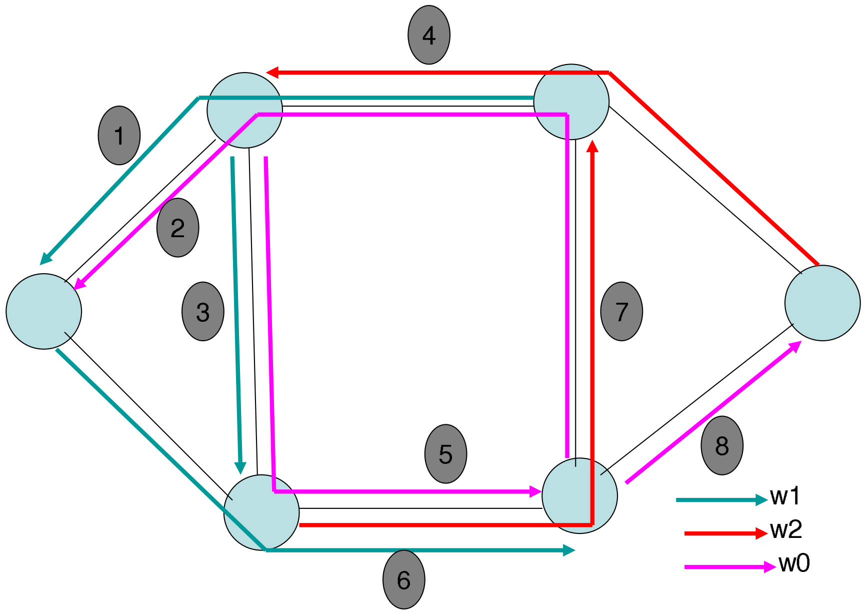

Figure 3.1: A network with eight routed lightpaths

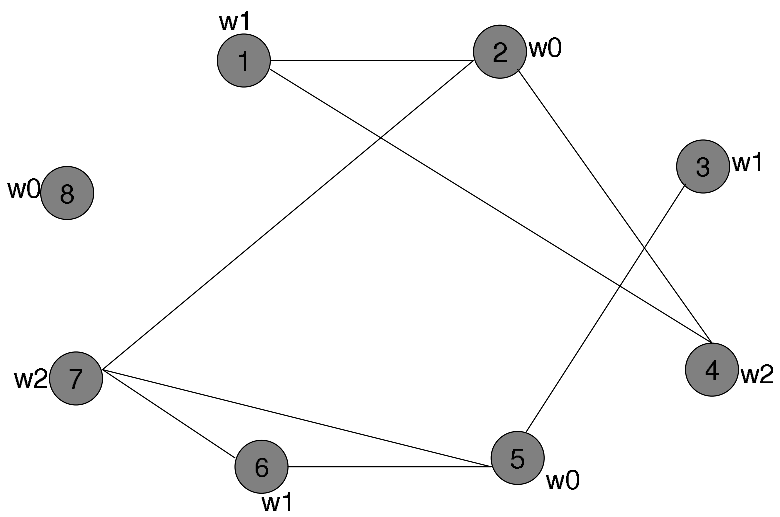

Figure 3.2: An auxiliary graph $G(V, E)$ for the lightpaths in Fig. 3.1

3.2 Lower Bound of Chromatic Number under The Domain of NP

Let $\omega(G)$ be the size of the maximum clique and $\delta(G)$ be the degree of the graph G,then the following inequality holds:

$$\omega(G) \leq \lambda(G) \leq \delta(G) + 1 \tag{3.1}$$

Assume that $|V(G)| = n$. Then the power set of $V(G)$ collects all possible subsets of the node set $V(G)$ whose cardinality is 2^n. To check whether a subset X of the node set $V(G)$ is a clique can be accomplished within $O(n^2)$ by checking whether for every pair of vertices $u, v \in X$, there exists an edge$(u,v) \in E(G)$. Hence, the time complexity to determine the size of maximum clique is found to be $O(2^n n^2)$.

The size of maximum clique defines the minimum number of wavelengths required to color all the lightpath requests available in the traffic matrix. The time to calculate the size of maximum clique is exponential with the number of nodes in $V(G)$ and thus it is not possible to determine the minimum number of wavelengths required to color all the lightpath requests in polynomial time. The optimal solution to the clique problem belongs to NP complexity class.

We select 3-SAT problem as a known NP-complete problem and reduce it to the clique problem. We wish to show that the reduction takes polynomial time and thus clique problem is NP-complete.

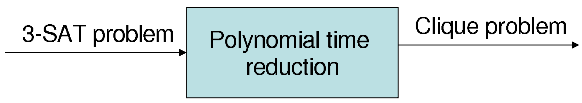

Figure 3.3: Reduction from 3-SAT problem to clique problem

The steps involved in proving a problem L is NP-complete are the following:

- Show that L is in NP.
- Select a known NP-complete problem, L'.
- Construct a reduction from L' to L.
- Show that the reduction takes polynomial time.

Based on the above steps, we wish to prove clique problem is NP-complete as explained below [11]:

- Step-1: we show that clique problem is NP.

  A non deterministic algorithm guesses a set of vertices $X \in V(G)$. Check for every pair of vertices $u, v \in X$, there exists an edge$(u,v) \in E(G)$. This step can be accomplished in polynomial time.

- Step-2: Select 3-SAT problem with k clauses in Conjunctive Normal Form (CNF) as a suitable NP-complete problem for reduction to the clique problem.
- Step-3: Show that 3-SAT problem reduces to the clique problem.
  - Let $\psi = C_1 \wedge C_2 \wedge C_3 \wedge .... \wedge C_k$ be a predicate in CNF with k clauses. Each clause C_i has exactly three variables denoted by $C_i = x_i^1 \vee x_i^2 \vee x_i^3$.
  - We construct a graph $G'(V', E')$ such that ψ is satisfiable if and only if G' has a clique of size k.
  - For each clause $C_i = x_i^1 \vee x_i^2 \vee x_i^3$, create vertices v_i^1, v_i^2, v_i^3. Collection of all such vertices for all the clauses in ψ defines $V'(G')$. Edges connect vertices provided the corresponding variables belong to different clauses and they are not true and complemented form of the same variable.
  - Construction of G' can be carried out in polynomial time. We assume that ψ has a satisfying assignment. Then each clause C_i contains at least one variable that is assigned true value. We pick one such true variable from each clause yielding a set of vertices X with elements k. We claim that X is a clique. For any two vertices $v_i^m, v_j^n \in X; i \neq j$ the corresponding variables x_i^m, x_j^n are mapped to true and cannot be complements. By the construction of G', the edge $(v_i^m, v_j^n) \in E'$.
- Step-4: The transformation can be carried out in polynomial time and hence clique problem is found to be NP-complete.

The proof shows that there does not exist any algorithm with a known polynomial time complexity to calculate the size of maximum clique for large instances of the graph G. As more lightpaths enter the system, the minimum number of wavelengths required to color them can not be determined optimally within polynomial time due to the computational constraints and memory limitation of scientific computers. Thus, heuristic approaches are adopted to solve the wavelength assignment part of the RWA problem.

3.3 Summary

In this chapter, we have proved the RWA problem to be NP-complete by performing a polynomial time reduction from the 3-SAT problem to clique problem. The size of maximum clique defines the minimum number of wavelengths required to establish all the lightpath requests. As the time required to calculate the size of maximum clique grows exponentially with the number of lightpath requests; it becomes impossible to determine the minimum number of wavelengths required to color all those lightpath requests in polynomial time. Thus, the optimal solution to maximum clique problem belongs to NP complexity class. The next chapter focuses on integer linear programming (ILP) formulations to model the RWA problem as an optimization problem.

Chapter 4

Multi-Objective Integer Linear Programming Formulation for RWA Problem

The RWA problem is a combinatorial optimization problem [57] and a wide range of optimization methods have been employed to solve this problem. The RWA problem can be modeled as an Integer Linear Programming (ILP) problem and solving the ILP is guaranteed to give the global optimum [5, 13, 31, 36, 39, 50, 61, 76]. However, due to the prohibitive computational efforts required for solving the ILP, novel heuristic techniques are generally employed for producing a feasible solution.

In this work, we consider the $Min - RWA$ problem [10, 39] and formulate the corresponding ILP as a multi-objective optimization problem. We assume that the network is static, circuit switched, and wavelength continuity constraint is maintained.

4.1 Notations Used

Notations used in the ILP formulation are defined as follows:

- V = Set of nodes in the network.
- E = Set of bidirectional fiber links in the network
- W = Set of non-interfering wavelength channels supported by every fiber link in the network
- (i, j) = Source-destination node pairs;$\{i, j\} \in V$

- D = Demand matrix of connection requests, where D_{ij} refers to a positive integral value stating the maximum demand between the node pair (i, j) and $D_{ij} = D_{ji}$
- $\omega^{-}(v)$ = Set of fiber links used by a lightpath to enter the node v
- $\omega^{+}(v)$ = Set of fiber links used by a lightpath to leave the node v

4.2 Variables Used

The variables used in the ILP formulation are defined as follows:

$$b_k(i,j) = \begin{cases} 1; if\ the\ lightpath\ \mathbf{k}\ between\ node\ pair\ (i,j)\ is\ established \\ 0; otherwise \end{cases}$$

$$b_k^w(i,j) = \begin{cases} 1; if\ the\ lightpath\ \mathbf{k}\ between\ node\ pair\ (i,j)\ is\ established\ with\ wavelength\ \mathbf{w} \\ 0; otherwise \end{cases}$$

$$b_k^{w,e}(i,j) = \begin{cases} 1; if\ the\ lightpath\ \mathbf{k}\ between\ node\ pair\ (i,j)\ is\ established\ with\ wavelength\ \mathbf{w} \\ on\ link\ \mathbf{e} \\ 0; otherwise \end{cases}$$

4.3 Multi-Objective ILP Formulation

In this section, we formulate the RWA problem as an multi-objective ILP problem. The lightpaths are grouped according to their source-destination node pairs. Let K be the set of ordered lightpath requests. Then K is interpreted as:

$$K = \bigcup_{(i,j)\in V\times V} K(i,j);\ K(i,j) = K(j,i)\ and\ i \neq j \tag{4.1}$$

where

$$|K| = \frac{\sum\limits_{i\in V}\sum\limits_{j\in V} D_{ij}}{2}$$

$$\left|K(i,j)\right| = \left|K(j,i)\right| = D_{ij} = D_{ji}$$

The lightpath requests in $K(i,j)$ and $K(j,i)$ are stated in Eq. 4.2, 4.3 respectively. A lightpath occupies the same wavelength in fibers with opposite direction through all links traversed by it between the node pair (i,j) in order to accomplish bidirectional communication.

$$K(i,j) = \{k \in K | (\sum_{e \in \omega^-(i)} \sum_{w \in W} b_k^{w,e}(i,j) = 0) \wedge (\sum_{e \in \omega^+(j)} \sum_{w \in W} b_k^{w,e}(i,j) = 0)\} \tag{4.2}$$

$$K(j,i) = \{k \in K | (\sum_{e \in \omega^-(j)} \sum_{w \in W} b_k^{w,e}(j,i) = 0) \wedge (\sum_{e \in \omega^+(i)} \sum_{w \in W} b_k^{w,e}(j,i) = 0)\} \tag{4.3}$$

The objective functions that we wish to optimize are stated as below:

- **Minimizing the congestion of the most congested link in the network:**

$$Minimize \quad \max_{e \in E} \sum_{(i,j) \in V \times V : D_{ij} > 0} \sum_{k \in K(i,j)} \sum_{w \in W} b_k^{w,e}(i,j) \tag{4.4}$$

- **Minimizing the difference between most congested and least congested link in the network:**

$$Min \quad \{\max_{e \in E} \sum_{(i,j) \in V \times V : D_{ij} > 0} \sum_{k \in K(i,j)} \sum_{w \in W} b_k^{w,e}(i,j) - \min_{e \in E} \sum_{(i,j) \in V \times V : D_{ij} > 0} \sum_{k \in K(i,j)} \sum_{w \in W} b_k^{w,e}(i,j)\} \tag{4.5}$$

- **Minimizing the difference between most congested link and average congestion of all links in the network:**

$$Min \quad \{\max_{e \in E} \sum_{(i,j) \in V \times V : D_{ij} > 0} \sum_{k \in K(i,j)} \sum_{w \in W} b_k^{w,e}(i,j) - \frac{\sum_{(i,j) \in V \times V : D_{ij} > 0} \sum_{k \in K(i,j)} \sum_{e \in E} \sum_{w \in W} b_k^{w,e}(i,j)}{|E|}\} \tag{4.6}$$

- **Minimizing the maximum number of intermediate hops traversed:**

$$Minimize \quad \max_{k \in \bigcup_{(i,j): D_{ij} > 0} K(i,j)} \sum_{e \in E} \sum_{w \in W} b_k^{w,e}(i,j) \tag{4.7}$$

- **Minimizing the number of fiber links used to honor all the lightpaths:**

$$Minimize \quad \left| \{e \in E| \sum_{(i,j):D_{ij}>0} \sum_{k \in K(i,j)} \sum_{w \in W} b_k^{w,e}(i,j) > 0\} \right| \tag{4.8}$$

- **Minimizing the maximum route length:**

$$Minimize \quad \max_{k \in \bigcup_{(i,j):D_{ij}>0} K(i,j)} \sum_{e \in E} (d_e | \sum_{w \in W} b_k^{w,e}(i,j) > 0) \tag{4.9}$$

where d_e = delay associated with link e

- **Minimizing the total route length:**

$$Minimize \quad \sum_{(i,j):D_{ij}>0} \sum_{k \in K(i,j)} \sum_{e \in E} (d_e | \sum_{w \in W} b_k^{w,e}(i,j) > 0) \tag{4.10}$$

where d_e = delay associated with link e

The above objective functions are subjected to the following constraints:

- **Wavelength continuity constraint:**

$$\sum_{w \in W} b_k^w(i,j) \leq 1; \forall k \in K(i,j) \ and \ \forall (i,j) \in V \times V : D_{ij} > 0 \tag{4.11}$$

The wavelength continuity constraint enforces a lightpath to use the same wavelength among all the links traversed between the source-destination node pair.

- **Wavelength distinct constraint:**

$$\sum_{(i,j) \in V \times V : D_{ij} > 0} \sum_{k \in K(i,j)} b_k^{w,e}(i,j) \leq 1; \forall w \in W \ and \ \forall e \in E \tag{4.12}$$

A distinct wavelength of a distinct fiber link can be at most allocated to a single lightpath.

- **Demand constraint:**

$$\sum_{k \in K(i,j)} b_k(i,j) \leq D_{ij}; \forall (i,j) \in V \times V : D_{ij} > 0 \tag{4.13}$$

The number of established lightpaths between a node pair should not exceed its maximum demand.

- **Integer constraint:**

$$b_k(i,j), b_k^w(i,j), b_k^{w,e}(i,j) \in \{0,1\} \tag{4.14}$$

The required variables of the ILP should keep integral values only.

- **Wavelength reservation constraint:**

$$\sum_{k\in K(i,j)} \sum_{e\in\omega^-(v|v\in V-\{i,j\})} b_k^{w,e}(i,j) - \sum_{k\in K(i,j)} \sum_{e\in\omega^+(v|v\in V-\{i,j\})} b_k^{w,e}(i,j) = 0; \quad \forall (i,j) \in V\times V : D_{ij} > 0 \; and \; w \in W \tag{4.15}$$

The number of lightpaths between a node pair (i,j) entering an intermediate node v with a wavelength w must be equal to the number lightpaths between (i,j) leaving the intermediate node v with wavelength w.

- **Consistency constraint:**

$$b_k(i,j) \geq b_k^w(i,j) \geq b_k^{w,e}(i,j) \tag{4.16}$$

A blocked lightpath can not claim network resources in terms of fiber links and free wavelengths.

- **Hop count constraint:**

$$\sum_{e\in E}\sum_{w\in W} b_k^{w,e}(i,j) \leq H; \max_{(i,j)\in V\times V}\{d(i,j)\} \leq H \leq |V| \tag{4.17}$$

where $d(i,j)$ is the distance between the node pair (i,j) and calculated as the minimum number of edges in a path from node i to node j.

The optimization objective stated in Eq. 4.7 enforces H to possess an integral value as minimum as possible.

- **No looping constraint around the source node:**

$$\sum_{k\in K(i,j)}\sum_{e\in\omega^-(i)}\sum_{w\in W} b_k^{w,e}(i,j) = 0; \forall (i,j) \in V\times V : D_{ij} > 0 \tag{4.18}$$

The set of incoming fiber links denoted as $\omega^-(i)$ is used by a lightpath between node pair (i,j) to enter the source node i. Nullifying the set $\omega^-(i)$ for all such lightpaths between node pair (i,j) ensures the prevention of loops around the source node.

- **No looping constraint around the destination node:**

$$\sum_{k \in K(i,j)} \sum_{e \in \omega^+(j)} \sum_{w \in W} b_k^{w,e}(i,j) = 0; \forall (i,j) \in V \times V : D_{ij} > 0 \tag{4.19}$$

The set of outgoing fiber links denoted as $\omega^+(j)$ is used by a lightpath between node pair (i,j) to leave the destination node j. Nullifying the set $\omega^+(j)$ for all such lightpaths between node pair (i,j) ensures the prevention of loops around the destination node.

- **No looping constraint around the intermediate nodes:**

$$\sum_{e \in \omega^-(v): v \in V - \{i,j\}} \sum_{w \in W} b_k^{w,e}(i,j) \leq 1; \forall k \in K(i,j) and \forall (i,j) \in V \times V : D_{ij} > 0 \tag{4.20}$$

$$\sum_{e \in \omega^+(v): v \in V - \{i,j\}} \sum_{w \in W} b_k^{w,e}(i,j) \leq 1; \forall k \in K(i,j) and \forall (i,j) \in V \times V : D_{ij} > 0 \tag{4.21}$$

$$\begin{gathered} \sum_{e \in \omega^+(v): v \in V - \{i,j\}} \sum_{w \in W} b_k^{w,e}(i,j) - \sum_{e \in \omega^-(v): v \in V - \{i,j\}} \sum_{w \in W} b_k^{w,e}(i,j) = 0; \\ \forall k \in K(i,j) and \forall (i,j) \in V \times V : D_{ij} > 0 \end{gathered} \tag{4.22}$$

A lightpath may enter and leave an intermediate node at most one time to avoid creation of loops around the intermediate nodes.

We can modify the above ILP formulation by eliminating the variable $b_k(i,j)$ resulting in an ILP with better space complexity. For the sake of brevity, we outline the modifications only. We can modify the demand constraint, integer constraint, and the consistency constraint of the above ILP as follows:

- **Demand constraint:**

$$\sum_{k \in K(i,j)} \sum_{w \in W} b_k^w(i,j) \leq D_{ij}; \forall (i,j) \in V \times V : D_{ij} > 0 \tag{4.23}$$

- **Integer constraint:**

$$b_k^w(i,j), b_k^{w,e}(i,j) \in \{0,1\} \tag{4.24}$$

- **Consistency constraint:**

$$b_k^w(i,j) \geq b_k^{w,e}(i,j) \tag{4.25}$$

4.3.1 Lemma: 1

Under wavelength continuity constraint, the congestion of the most congested link in the network defines the lower bound on the number of wavelengths required to establish all the lightpaths in a given demand matrix.

Proof: In a network, the most congested link specify the minimum number of distinct wavelengths required to establish a set of lightpath requests. The lemma is illustrated with an example below:

In the following exemplary network, the establishment of three lightpath requests requires three distinct wavelength colors while keeping the congestion level at two, among all the links in the network. It reveals that the congestion level of the most congested link in the network defines the lower bound on the actual number of wavelengths required to establish all the lightpath requests in the traffic matrix.

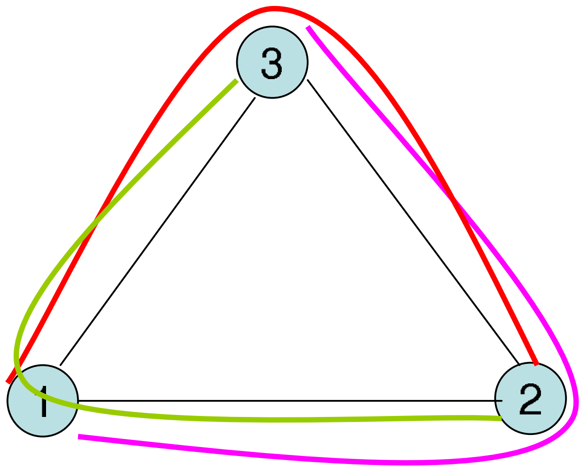

Figure 4.1: An exemplary network

The lemma may be stated by the following formulation:

$$\max_{e \in E} \sum_{(i,j) \in V \times V : D_{ij} > 0} \sum_{k \in K(i,j)} \sum_{w \in W} b_k^{w,e}(i,j) \leq \sum_{(i,j) \in V \times V : D_{ij} > 0} \sum_{k \in K(i,j)} \sum_{w \in W} b_k^{w}(i,j) \tag{4.26}$$

4.4 Summary

In this chapter, we formulated a multi objective ILP for the RWA problem. The stated objective functions optimize a number of network parameters such as congestion, route length, hop count and the total number of fiber links used to honor all the lightpath requests. Solving the multi objective ILP; we wish to establish loop free lightpaths that have shorter set-up time, lower congestion among the individual connections, and lesser accumulated crosstalk while traversing between source-destination node pairs. In the next chapter the formulated ILP is solved using GA to produce a feasible solution in polynomial time.

Chapter 5

Simulation & Results

In this chapter, we made an attempt to solve the proposed multi-objective optimization problem using genetic algorithm [1, 19, 23, 49, 75] which are a class of probabilistic searching algorithms based on the mechanism of biological evolution. We use a GA-based RWA algorithm [56] and simulate on NSFNET & ARPANET.

5.1 The GA-Based RWA Algorithm

The steps of the genetic algorithm used to solve our proposed ILP is explained below:

(i) **The Chromosome Structure:** We encode the chromosome as a vector of vectors $\begin{bmatrix} p_1 \\ : \\ p_{|K|} \end{bmatrix}$ where each vector p_i is a lightpath represented as $\begin{pmatrix} n_{i0} & ... & n_{ih(i)} \end{pmatrix}; n_{i0}, ...n_{ih(i)} \in V$ and $h(i)$ defines the number of hops traversed by the lightpath p_i.

(ii) **Initial Population:** For every lightpath (s_i, d_i), find the minimum cost path p_i using Dijkstra's algorithm. All p_i's taken together form the first chromosome of the first generation. For each fiber link $(n_{ij}, n_{i(j+1)})$ in every p_i, disable one link at a time and find minimum cost paths to form a new chromosome. Repeat the above process until the population size is reached.

(iii) **Fitness function:** The fitness function is the target function to be maximized and is used to discriminate the chromosomes such that better chromosomes will have better chance to propagate their genetic materials to the successive generations.

The symbols used to define the fitness functions are:

con= Congestion of the most congested link in the network and defines the network load.

l_con= Congestion of the least congested link in the network.

a_con= Average congestion of all links in the network.

max_h_count= Maximum number of hops traversed by a lightpath in a chromosome.

max_r_length= Maximum delay of a lightpath in a chromosome.

tot_r_length= Total delay in establishing all the static lightpaths.

tot_fib= Total number of fibers used to honor all the lightpaths in a chromosome.

d=Maximum delay of a link in the network.

Different fitness functions to implement a single objective genetic algorithm is defined as follows:

$$y_1 = 1 - \frac{con}{|K|} \tag{5.1}$$

$$y_2 = 1 - \frac{con - l\_con}{|K|} \tag{5.2}$$

$$y_3 = 1 - \frac{con - a\_con}{|K|} \tag{5.3}$$

The fitness functions y_1, y_2 and y_3 optimize the primary network design objectives stated in Eq. 4.4, Eq. 4.5 and Eq. 4.6 respectively.

The above stated fitness functions are modified as defined below by considering different secondary objectives to implement a multi-objective genetic algorithm . The presented multi-objective GA implements a priori preference articulation in order to measure tradeoffs between different objectives. A priori preferences are used to construct weighted sum fitness functions prior to optimization.

$$\begin{aligned} y_4 = 1 - 0.90\frac{con}{|K|} - 0.07\frac{tot\_r\_length}{d|K|(|V|-1)} - 0.01\frac{max\_r\_length}{d(|V|-1)} \\ -0.01\frac{max\_h\_count}{|V|-1} - 0.01\frac{tot\_fib}{|E|} \end{aligned} \tag{5.4}$$

$$\begin{aligned} y_5 = 1 - 0.90\frac{con-l\_con}{|K|} - 0.07\frac{tot\_r\_length}{d|K|(|V|-1)} - \\ 0.01\frac{max\_r\_length}{d(|V|-1)} - 0.01\frac{max\_h\_count}{|V|-1} - 0.01\frac{tot\_fib}{|E|} \end{aligned} \tag{5.5}$$

$$\begin{aligned} y_6 = 1 - 0.90\frac{con-a\_con}{|K|} - 0.07\frac{tot\_r\_length}{d|K|(|V|-1)} - \\ 0.01\frac{max\_r\_length}{d(|V|-1)} - 0.01\frac{max\_h\_count}{|V|-1} - 0.01\frac{tot\_fib}{|E|} \end{aligned} \tag{5.6}$$

The fitness function y_4 optimizes the primary design objective stated in Eq. 4.4 along with the secondary objectives stated in Eq. 4.7, 4.8, 4.9 and 4.10. Similarly, the fitness functions y_5 and y_6 optimize the primary design objectives stated in Eq. 4.5 and Eq. 4.6 respectively, with the secondary objectives stated in Eq. 4.7, 4.8, 4.9 and 4.10.

(iv) **Selection of chromosomes for next generation:** The chromosomes of the next generation are selected from the current population by a spinning roulette wheel method.

The fitness values of the chromosomes in the current population is normalized as follows.

$$f(g) = \frac{f(g) - min(f(g))}{max(f(g)) - min(f(g))} \tag{5.7}$$

where

$f(g)$ = fitness of the chromosome g

$min(f(g))$ = The chromosome with least fitness in the current population

$max(f(g))$ = The chromosome with highest fitness in the current population

The probability that a chromosome g is selected from the current population is given as $\Pr_g = \frac{f(g)}{\sum_g f(g)}$

The cumulative probability of the chromosome g is calculated as $PR_g = \sum_{u=1}^{g} \Pr_u$

Then, spin the roulette wheel, and for each spin, a random number v is generated such that $v \in \{0,1\}$.

If $PR_{g-1} < v \leq PR_g$; then select the chromosome g for the next population.

(v) **Crossover:** In the selected generation, with a certain crossover rate a chromosome is selected for mating with another chromosome. According to a crossover ratio, calculate the number of lightpaths that will be modified. These lightpaths are randomly chosen and exchanged between the selected chromosomes.

(vi) **Mutation:** In the selected generation, a chromosome is mutated with a certain mutation rate. According to a mutation ratio, calculate the number of lightpaths that will be modified. For each such lightpath $p_i = [n_{i0}, n_{i1}, ..., n_{ih_i}]$, randomly pick two adjacent nodes n_{ij} and $n_{i(j+1)}$. Disable the fiber link between the two nodes and remove all the nodes n_{il} such that $l < j$ and $l > j+1$. Then calculate the minimum cost path between n_{ij} and $n_{i(j+1)}$ and replace the corresponding portion in p_i using the new path.

Selection schemes primarily predict the convergence characteristics of a GA within a deterministic (noiseless) environment. The following effects of different genetic operators explain the convergence characteristics of the above GA used to solve the proposed ILP formulation:

- Roulette spinning wheel selection method drives the GA to improve the population fitness over succeeding generations. The statistical effect of roulette spinning wheel selection policy is: the best chromosomes get more copies, the average stay even and the worst die off.
- The crossover operator tends to cause the GA to converge on a good but sub-optimal solution.
- The mutation operator induces a random walk through the search space and helps to avoid early convergence.

5.2 Simulation Work

We consider a 20 nodes ARPANET and a 16 nodes NSFNET as shown in Fig. 5.1 and 5.2 respectively. Each fiber link in these networks is labeled with a delay which is measured in terms of seconds. The set of lightpath requests that we considered for ARPANET is shown in Table 5.1. The value of different parameters of GA used in the simulation are shown in Table 5.2. There is no limit on the number of wavelengths a fiber can carry; however an attempt is made to find the minimum possible number required to honor a given demand matrix.

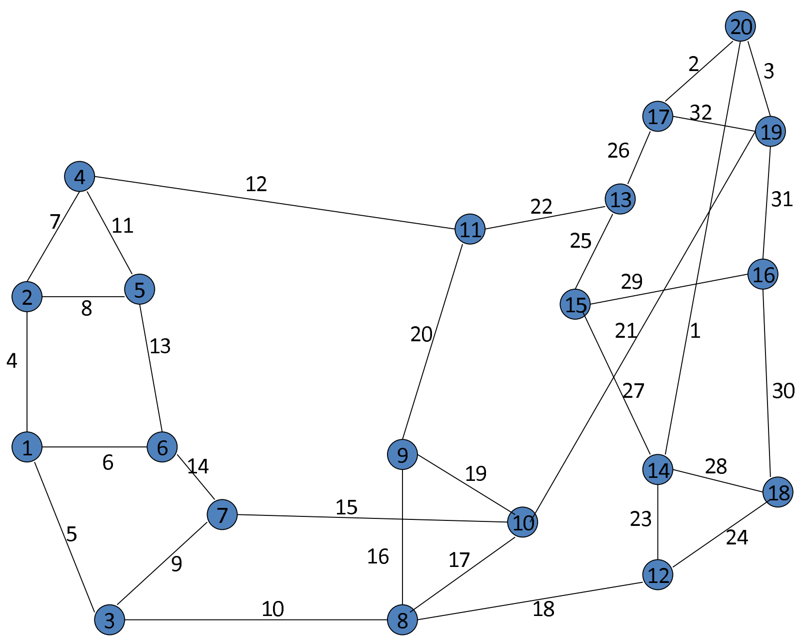

Figure 5.1: Advanced Research Project Agency Network (ARPANET)

Table 5.1: Demand set of static lightpath requests in ARPANET

Lightpath	Minimum cost path
n10-n13	n10-n19-n20-n17-n13
n15-n7	n15-n14-n20-n19-n10-n7
n7-n5	n7-n3-n1-n2-n5
n10-n1	n10-n7-n3-n1
n15-n14	n15-n14
n10-n8	n10-n8
n8-n15	n8-n12-n14-n15
n2-n10	n2-n1-n3-n7-n10
n3-n9	n3-n8-n9
n9-n20	n9-n10-n19-n20

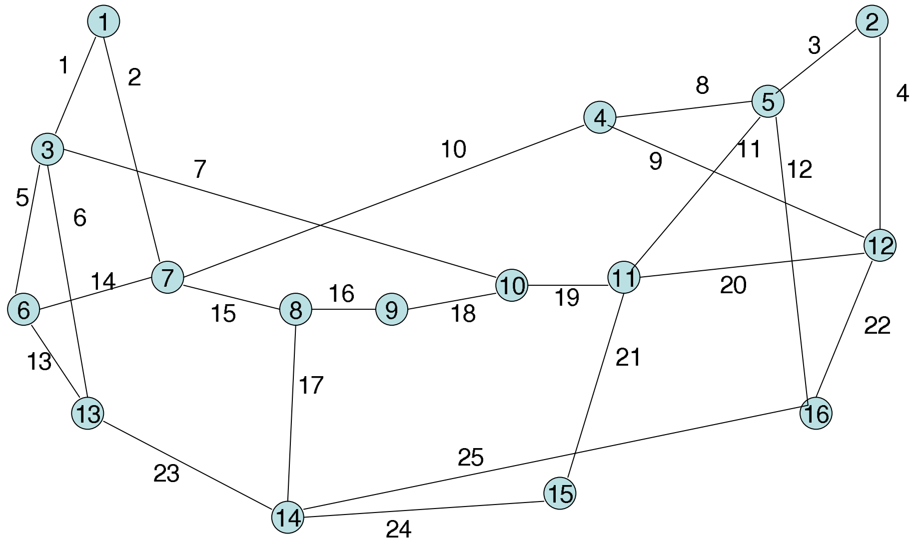

Figure 5.2: National Science Foundation Network (NSFNET)

Table 5.2: Parameters of the GA and their values

Parameters of the GA	Values
Population size	50
Maximum number of generations	100
Crossover probability	0.5
Mutation probability	0.1
Crossover ratio	0.2
Mutation ratio	0.2

The performance of the single objective genetic algorithm under different fitness functions is shown in Table 5.3. The lightpaths established using the fitness functions y_1, y_2 and y_3 is shown in Table 5.4.

Table 5.3: Performance comparison of single objective GA under different fitness functions

Single objective fitness functions	congestion	total delay (in seconds)	maximum hops traversed	Number of fibers used	Maximum delay (in seconds)
$fitness\ function\ y_1$	02	473	6	21	100
$fitness\ function\ y_2$	02	433	6	22	68
$fitness\ function\ y_3$	03	793	10	29	178

Table 5.4: Establishment of lightpath requests in ARPANET using fitness functions y_1, y_2 & y_3

Lightpath	Allocated Routes		
	y_1	y_2	y_3
n10-n13	n10-n19-n20-n17-n13	n10-n9-n11-n13	n10-n8-n12-n18-n16-n19-n17-n13
n15-n7	n15-n14-n12-n8-n10-n7	n15-n14-n20-n19-n10-n7	n15-n16-n18-n14-n20-n19-n10-n7
n7-n5	n7-n3-n1-n2-n5	n7-n3-n1-n2-n5	n7-n6-n1-n2-n5
n10-n1	n10-n7-n3-n1	n10-n7-n6-n1	n10-n7-n3-n8-n9-n11-n4-n5-n6-n1
n15-n14	n15-n13-n17-n20-n14	n15-n13-n17-n20-n14	n15-n13-n17-n20-n14
n10-n8	n10-n8	n10-n8	n10-n8
n8-n15	n8-n12-n14-n15	n8-n12-n14-n15	n8-n12-n18-n14-n15
n2-n10	n2-n4-n11-n9-n10	n2-n1-n3-n8-n10	n2-n1-n3-n7-n6-n5-n4-n11-n9-n10
n3-n9	n3-n8-n9	n3-n8-n9	n3-n8-n9
n9-n20	n9-n10-n19-n20	n9-n10-n19-n20	n9-n10-n19-n20

Similarly, the performance of the multi objective genetic algorithm under different fitness functions is shown in Table 5.5. The allocation of routes to the lightpath requests using the fitness functions y_4, y_5 and y_6 is shown in Table 5.6.

Table 5.5: Performance comparison of multi objective GA under different fitness functions

Multi objective fitness functions	congestion	total delay (in seconds)	maximum hops traversed	Number of fibers used	Maximum delay (in seconds)
$fitness\ function\ y_4$	02	421	6	18	83
$fitness\ function\ y_5$	02	431	6	21	101
$fitness\ function\ y_6$	03	599	10	25	116

Table 5.6: Establishment of lightpath requests in ARPANET using fitness functions y_4, y_5 & y_6

Lightpath	Allocated Routes		
	y_4	y_5	y_6
n10-n13	n10-n9-n11-n13	n10-n19-n20-n17-n13	n10-n19-n20-n17-n13
n15-n7	n15-n14-n20-n19-n10-n7	n15-n13-n11-n9-n10-n7	n15-n14-n12-n8-n10-n7
n7-n5	n7-n3-n1-n2-n5	n7-n3-n1-n2-n5	n7-n3-n1-n2-n4-n5
n10-n1	n10-n7-n6-n1	n10-n7-n6-n1	n10-n7-n6-n5-n4-n11-n9-n8-n3-n1
n15-n14	n15-n14	n15-n14	n15-n13-n17-n20-n14
n10-n8	n10-n8	n10-n8	n10-n8
n8-n15	n8-n9-n11-n13-n15	n8-n12-n14-n15	n8-n12-n18-n14-n15
n2-n10	n2-n1-n3-n8-n10	n2-n1-n3-n8-n10	n2-n4-n11-n9-n10
n3-n9	n3-n8-n9	n3-n8-n9	n3-n8-n9
n9-n20	n9-n10-n19-n20	n9-n10-n19-n20	n9-n10-n19-n20

From the above tables, it is observed that the number of fibers used, total delay and maximum delay in multi objective GA is lesser than single objective GA.

We increased the number of lightpath requests and studied the various parameters of interest for single objective and multi objective GA. We plot the congestion, total set up time, maximum set up time, maximum hops traversed, total number of fibers used, execution time for a single objective GA in Fig. 5.3, 5.4, 5.5, 5.6, 5.7, 5.8 respectively. The corresponding plots for multi objective GA are shown in Fig. 5.9, 5.10, 5.11, 5.12, 5.13, 5.14, respectively.

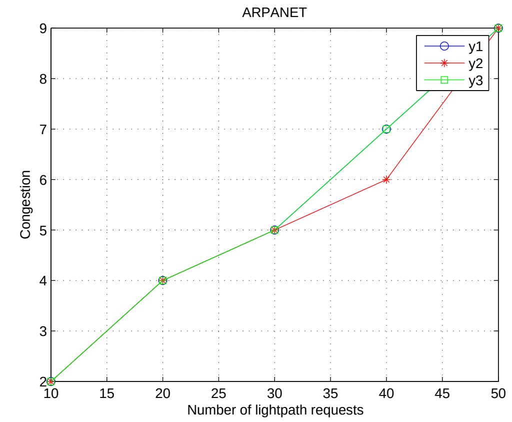

Figure 5.3: Optimization of congestion using single objective GA

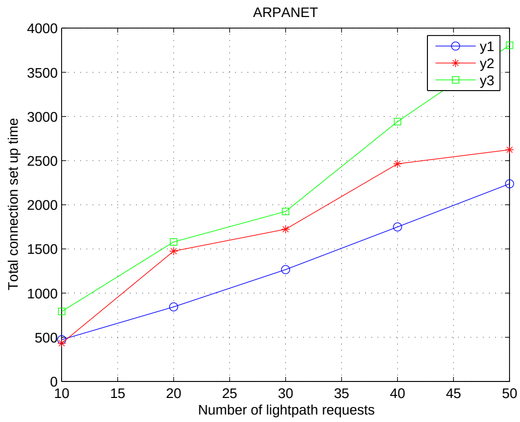

Figure 5.4: Optimization of total setup time using single objective GA

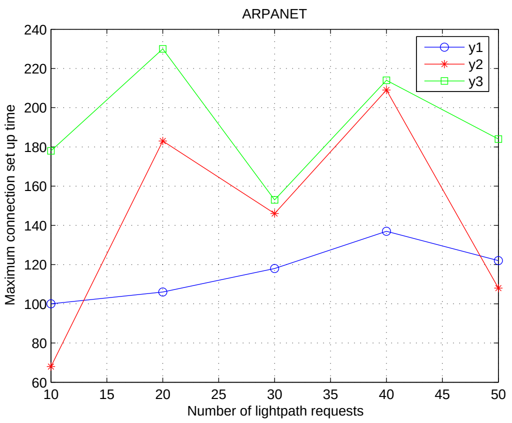

Figure 5.5: Optimization of maximum setup time using single objective GA

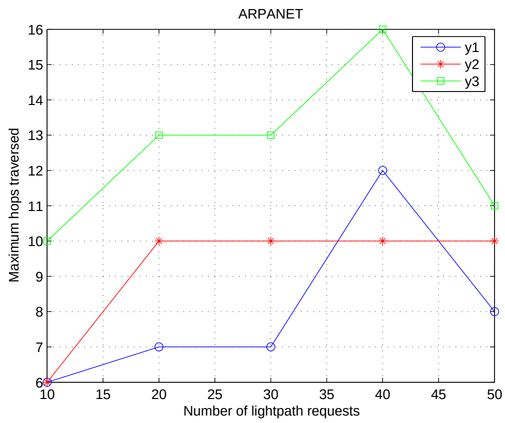

Figure 5.6: Optimization of maximum hops traversed using single objective GA

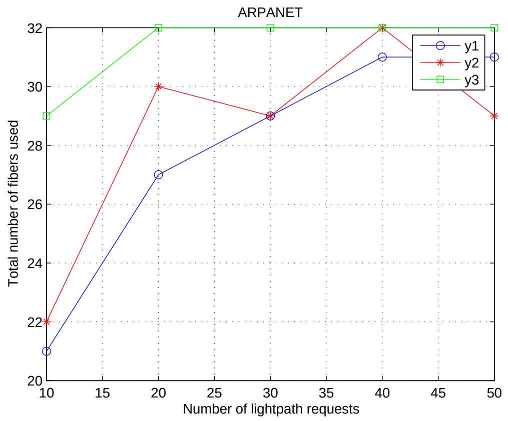

Figure 5.7: Optimization of total number of used fibers using single objective GA

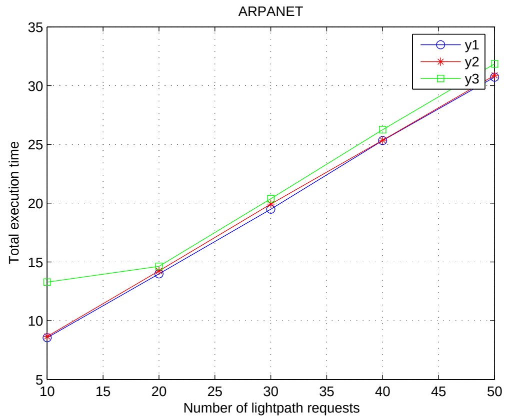

Figure 5.8: Comparison of execution time of single objective GA with different fitness functions

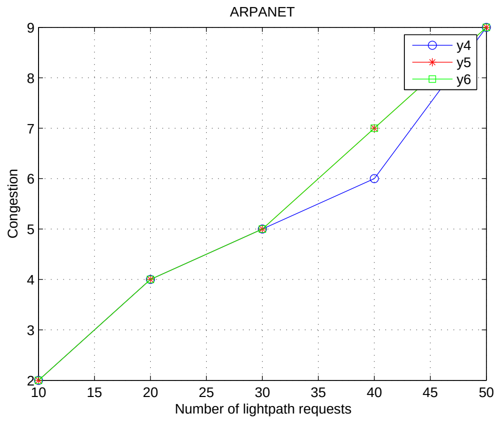

Figure 5.9: Optimization of congestion using multi objective GA

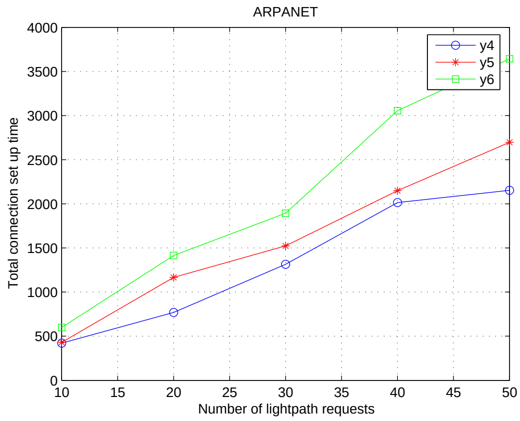

Figure 5.10: Optimization of total setup time using multi objective GA

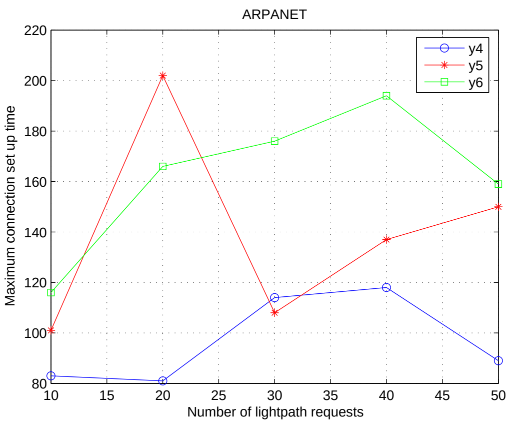

Figure 5.11: Optimization of maximum setup time using multi objective GA

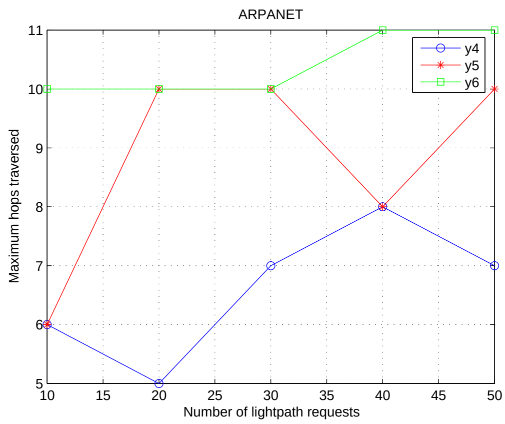

Figure 5.12: Optimization of maximum hops traversed using multi objective GA

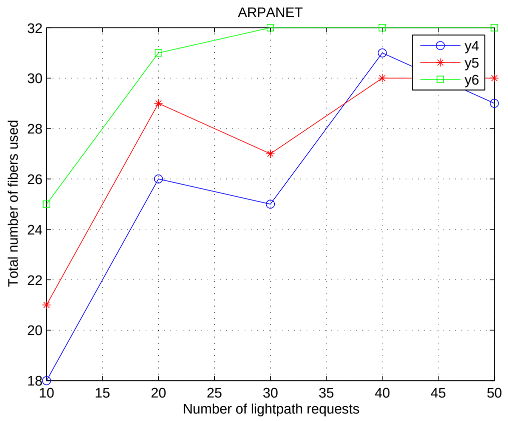

Figure 5.13: Optimization of total number of used fibers using multi objective GA

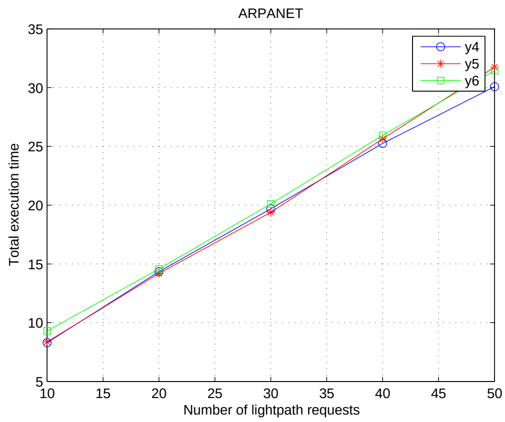

Figure 5.14: Comparison of execution time of multi objective GA with different fitness functions

Next, we simulated in NSFNET. The demand set of lightpaths used in the simulation is shown in Table 5.7.

Table 5.7: Demand set of static lightpath requests in NSFNET

Lightpath	Minimum cost path
n4-n5	n4-n5
n5-n12	n5-n-2-n12
n12-n2	n12-n2
n2-n4	n2-n5-n4
n3-n11	n3-n10-n11
n11-n15	n11-n15
n15-n10	n15-n11-n10
n10-n3	n10-n3
n6-n13	n6-n3-n13
n13-n14	n13-n14
n14-n16	n14-n16
n16-n6	n16-n5-n4-n7-n1-n3-n6
n1-n7	n1-n7
n7-n8	n7-n8
n8-n9	n8-n9
n9-n1	n9-n10-n3-n1

The performance of the single objective genetic algorithm under different fitness functions is shown in Table 5.8. The allocation of routes to the lightpath requests using the fitness functions y_1, y_2 and y_3 is shown in Table 5.9.

Similarly, the performance of the multi objective genetic algorithm under different fitness functions is shown in Table 5.10. The allocation of routes to the lightpath requests listed using the fitness functions y_4, y_5 and y_6 is shown in Table 5.11.

Table 5.8: Performance comparison of single objective GA under different fitness functions

Single objective fitness functions	congestion	total delay (in seconds)	maximum hops traversed	Number of fibers used	Maximum delay (in seconds)
fitness function y_1	02	310	4	14	61
fitness function y_2	02	350	7	14	71
fitness function y_3	02	402	08	22	72

Table 5.9: Establishment of lightpath requests in NSFNET using fitness functions y_1, y_2 & y_3

Lightpath	**Allocated Routes**		
	y_1	y_2	y_3
n4-n5	n4-n5	n4-n5	n4-n5
n5-n12	n5-n2-n12	n5-n2-n12	n5-n2-n12
n12-n2	n12-n2	n12-n2	n12-n2
n2-n4	n2-n5-n4	n2-n5-n4	n2-n5-n11-n12-n4
n3-n11	n3-n10-n11	n3-n1-n7-n8-n9-n10-n11	n3-n10-n11
n11-n15	n11-n15	n11-n15	n11-n5-n16-n14-n15
n15-n10	n15-n11-n10	n15-n11-n10	n15-n11-n10
n10-n3	n10-n3	n10-n3	n10-n3
n6-n13	n6-n-3-n13	n6-n13	n6-n3-n13
n13-n14	n13-n14	n13-n14	n13-n14
n14-n16	n14-n16	n14-n16	n14-n16
n16-n6	n16- n14-n13-n6	n16-n14-n13-n6	n16-n5-n4-n7-n1-n3-n13-n6
n1-n7	n1-n7	n1-n7	n1-n7
n7-n8	n7-n8	n7-n8	n7-n8
n8-n9	n8-n9	n8-n9	n8-n9
n9-n1	n9-n8-n7-n1	n9-n10-n3-n1	n9-n8-n7-n6-n3-n1

Table 5.10: Performance comparison of multi objective GA under different fitness functions

Multi objective fitness functions	congestion	total delay (in seconds)	maximum hops traversed	Number of fibers used	Maximum delay (in seconds)
fitness function y_4	02	328	6	16	61
fitness function y_5	02	308	5	13	59
fitness function y_6	02	500	9	21	130

We increased the number of lightpath requests and studied the various parameters of interest for single objective and multi objective GA. We plot the congestion, total set up time, maximum set up time, maximum hops traversed, total number of fibers used, execution time for a single objective GA in Fig. 5.15, 5.16, 5.17, 5.18, 5.19, 5.20 respectively. The corresponding plots for multi objective GA are shown in Fig. 5.21, 5.22, 5.23, 5.24, 5.25, 5.26, respectively.

Table 5.11: Establishment of lightpath requests in NSFNET using fitness functions y_4, y_5 & y_6

Lightpath	**Allocated Routes**		
	y_4	y_5	y_6
n4-n5	n4-n5	n4-n5	n4-n5
n5-n12	n5-n2-n12	n5-n2-n12	n5-n2-n12
n12-n2	n12-n2	n12-n2	n12-n2
n2-n4	n2-n5-n4	n2-n5-n4	n2-n5-n11-n12-n4
n3-n11	n3-n10-n11	n3-n10-n11	n3-n1-n7-n8-n9-n10-n11
n11-n15	n11-n15	n11-n15	n11-n5-n16-n14-n15
n15-n10	n15-n11-n10	n15-n11-n10	n15-n11-n10
n10-n3	n10-n3	n10-n3	n10-n3
n6-n13	n6-n3-n13	n6-n3-n13	n6-n3-n13
n13-n14	n13-n14	n13-n14	n13-n14
n14-n16	n14-n16	n14-n16	n14-n16
n16-n6	n16-n14-n13-n6	n16-n14-n13-n3-n6	n16-n5-n4-n12-n11-n15- n14- n13-n6
n1-n7	n1-n7	n1-n7	n1- n7
n7-n8	n7-n8	n7-n8	n7-n8
n8-n9	n8-n9	n8-n9	n8-n9
n9-n1	n9-n8-n7-n6-n3-n1	n9-n8-n7-n1	n9- n10- n3- n1

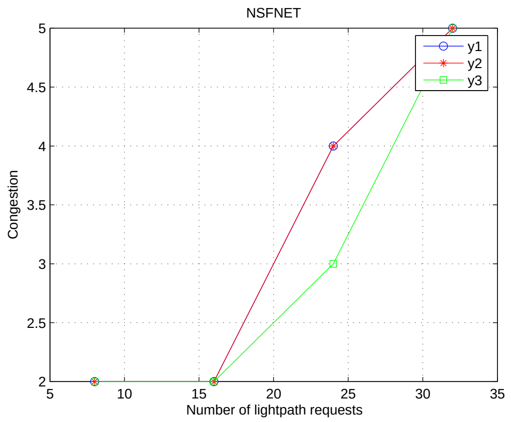

Figure 5.15: Optimization of congestion using single objective GA

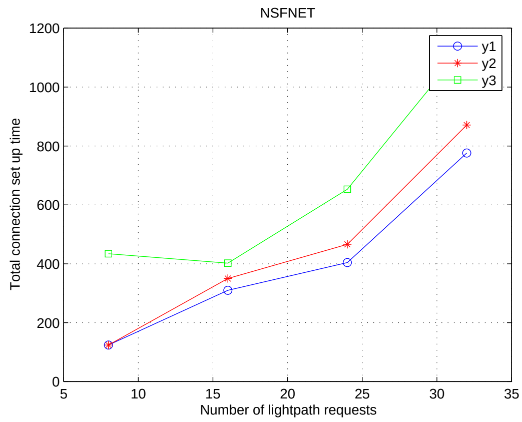

Figure 5.16: Optimization of total setup time using single objective GA

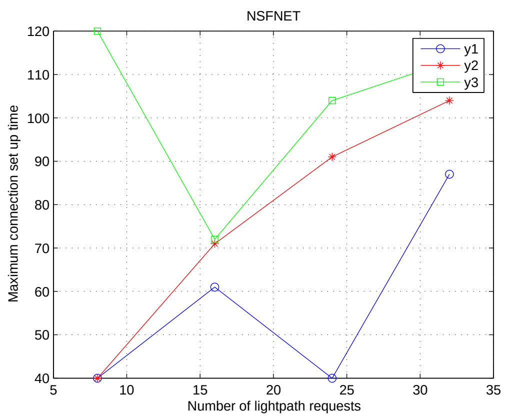

Figure 5.17: Optimization of maximum setup time using single objective GA

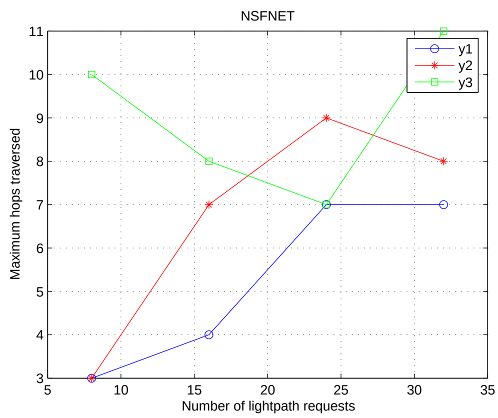

Figure 5.18: Optimization of maximum hops traversed using single objective GA

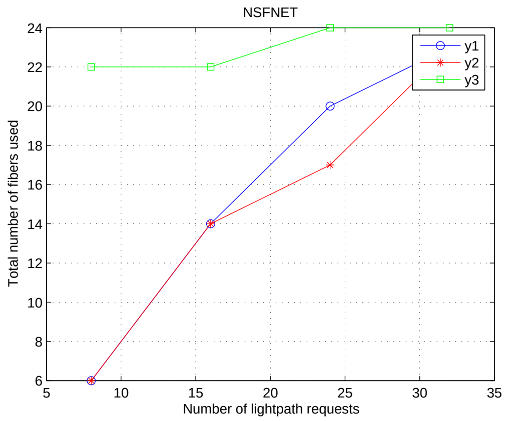

Figure 5.19: Optimization of total number of used fibers using single objective GA

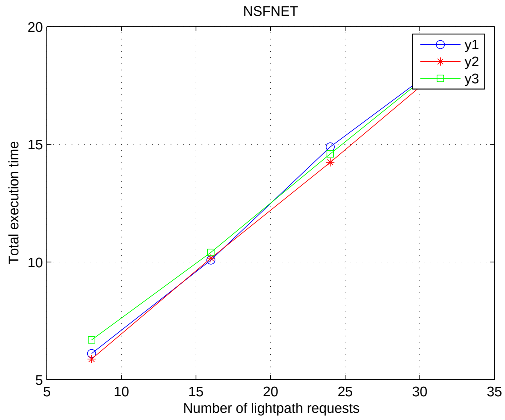

Figure 5.20: Comparison of execution time of single objective GA with different fitness functions

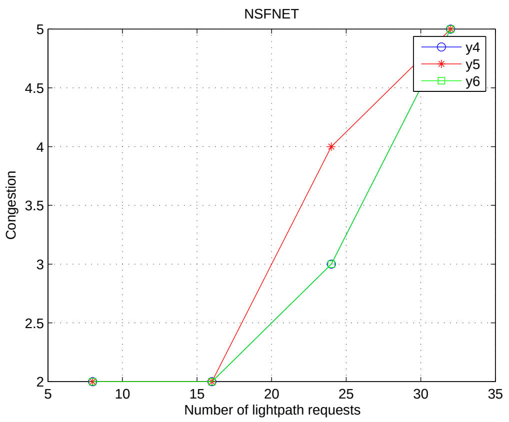

Figure 5.21: Optimization of congestion using multi objective GA

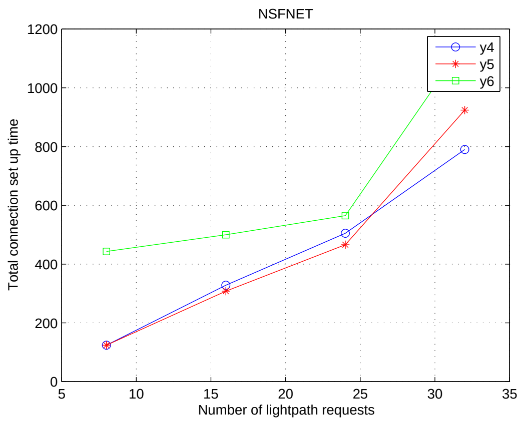

Figure 5.22: Optimization of total setup time using multi objective GA

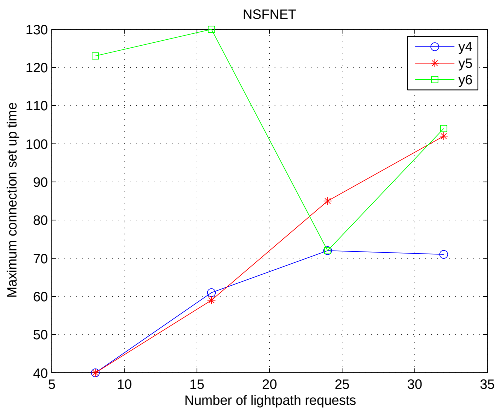

Figure 5.23: Optimization of maximum setup time using multi objective GA

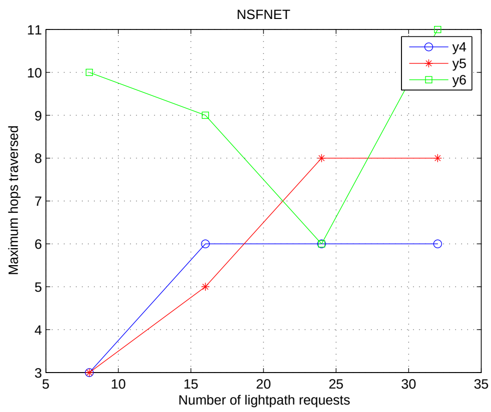

Figure 5.24: Optimization of maximum hops traversed using multi objective GA

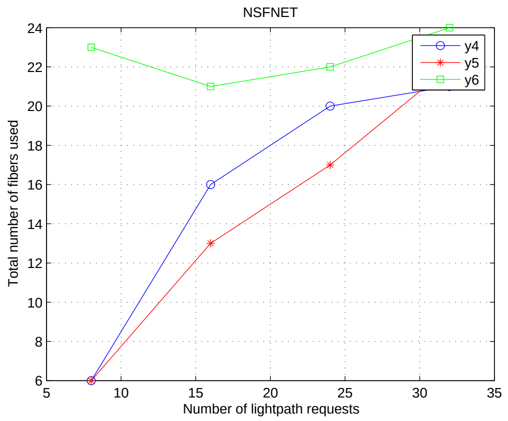

Figure 5.25: Optimization of total number of used fibers using multi objective GA

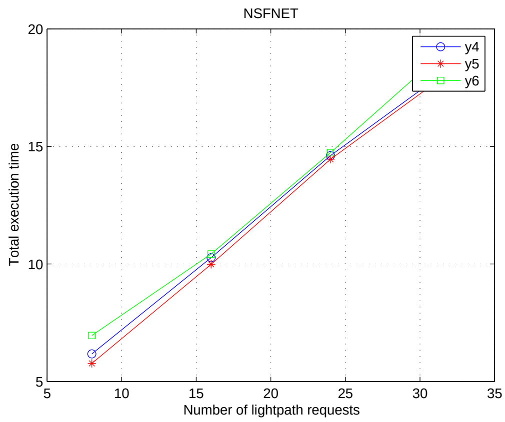

Figure 5.26: Comparison of execution time of multi objective GA with different fitness functions

5.3 Summary

The results show that the GA is effective in finding a reasonable solution in polynomial time. The performance of the GA is compared under various fitness functions. A rigorous simulation work reveals that the fitness function dealing with minimizing the difference between the most congested link and average congestion among all links in the network, produces inefficient results for most of the lightpath requests. The other two fitness functions dealing with minimizing the congestion of the most congested link and minimizing the difference between most and least congested link in the network respectively, maintains a trade-off while optimizing various network parameters.

Chapter 6

Conclusion and Future Work

The work in this thesis, addressed the routing and wavelength assignment problem in all optical networks. Our primary concern was to use nature inspired solutions, for instance, genetic algorithms as methods for solving routing and wavelength assignment in all optical networks. Section 6.1 deals with our contribution and Section 6.2 provides some scope for further development.

6.1 Contribution

Our contribution is mostly devoted to formulate the RWA problem as a multi objective ILP problem. The primary optimization objective is based on minimizing the number of wavelengths required to satisfy all lightpath requests in the demand matrix. We interpreted the RWA problem as an NP complete problem as the time to calculate the minimum wavelengths grows exponentially with the number of lightpath requests.

To fit the RWA problem in the multi objective optimization domain, we considered various network parameters such as congestion among the individual lightpath requests, connection set up time, the number of intermediate hops traversed and the number of fibers used to honor the established connection requests.

Accordingly, we formulated the RWA problem as a multi objective ILP problem and solved it using genetic algorithm in order to obtain a near optimal solution in polynomial time.

6.2 Future Work

The ILP formulations stated in **Chapter 4** are applicable to networks where wavelength continuity constraint is maintained.The following ILP is a modification of the previously proposed ILP in order to apply it in wavelength convertible networks [33, 46, 79, 80].

6.2.1 Modified ILP Formulation

In wavelength convertible networks; the intermediate routing nodes are capable of converting an incoming optical signal in one wavelength to an outgoing signal in another wavelength. In such networks, the wavelength continuity constraint can be relaxed and restated as follows:

$$\sum_{w \in W} b_k^w(i,j) \leq \delta;\ \forall k \in K(i,j), \forall (i,j) \in V \times V : D_{ij} > 0 \tag{6.1}$$

where δ denotes the upper bound on the number of wavelength converters that can be used by a lightpath and a small value on δ ensures less signal distortion.

In networks with sparse wavelength conversion capability, only a subset of routing nodes are equipped with wavelength converters. In such networks, the provision of converting an optical signal from one wavelength to another wavelength is restricted to the network nodes capable of wavelength conversion. The following enumeration states the usage of wavelength channels among the intermediate nodes:

- **At nodes without wavelength converters:**

$$b_k^{w,(e1|e1\in\omega^-(v|v\in V-\{i,j\}))}(i,j) = b_k^{w,(e2|e2\in\omega^+(v|v\in V-\{i,j\}))}(i,j) \tag{6.2}$$

- **At nodes equipped with wavelength converters:**

$$\sum_{w\in W} b_k^{w,(e1|e1\in\omega^-(v|v\in V-\{i,j\}))}(i,j) = \sum_{w\in W} b_k^{w,(e2|e2\in\omega^+(v|v\in V-\{i,j\}))}(i,j) \tag{6.3}$$

If all the routing nodes of the WDM network are equipped with limited range wavelength converters with degree of conversion Δ, then Eq. 6.3 may be split into the following two equations.

$$\sum_{w' \in W} b_k^{w',(e1|e1 \in \omega^-(v|v \in V-\{i,j\}))}(i,j) = b_k^{w,(e2|e2 \in \omega^+(v|v \in V-\{i,j\}))}(i,j); w-\Delta \le w' \le w+\Delta \tag{6.4}$$

$$b_k^{w,(e1|e1 \in \omega^-(v|v \in V-\{i,j\}))}(i,j) = \sum_{w' \in W} b_k^{w',(e2|e2 \in \omega^+(v|v \in V-\{i,j\}))}(i,j); w-\Delta \le w' \le w+\Delta \tag{6.5}$$

6.3 Further Issues

The following issues deserve more investigation for further development of this research work:

1. The performance of the genetic algorithm can be analyzed under different parameter values.

2. We can test run the genetic algorithm by using practical networks with demand uncertainty.

3. The performance of the genetic algorithm can be compared against other frequently used heuristics.

4. When the fiber links of an optical network support limited wavelength channels, the SLE problem can be remodeled as an Max-RWA problem to set up as many of lightpaths as possible for the connection requests.

5. The genetic algorithm can be extended to achieve fault tolerance in optical layer.

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